# Neutrinos:
## Candidates and Probes of Dark Matter


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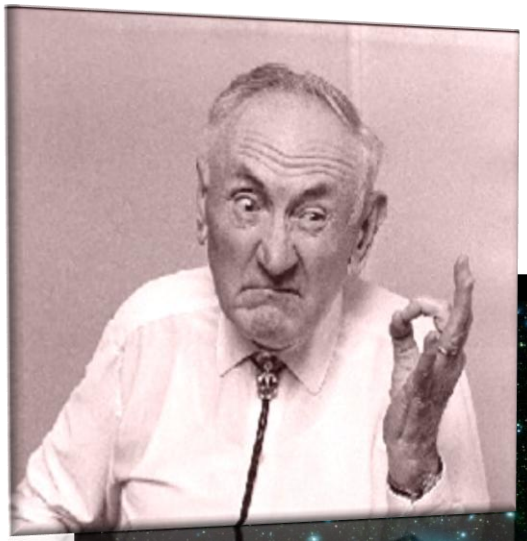
KICP Workshop
The impact of high-energy astrophysics experiments on cosmological physics

27-28 October, 2008

# Dark Matter: The Beginnings

1930s: Zwicky proposed **Dark Matter** to explain the mass to light ratio of Coma galaxy cluster



ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

**Nebulae as Gravitational Lenses**

F. ZWICKY

ON THE CLUSTERING OF NEBULAE

BY F. ZWICKY

NUCLEAR GOBLINS AND COSMIC GAMMA RAY BURST

F. ZWICKY

*COSMIC RAYS FROM SUPER-NOVAE*

BY W. BAADE AND F. ZWICKY

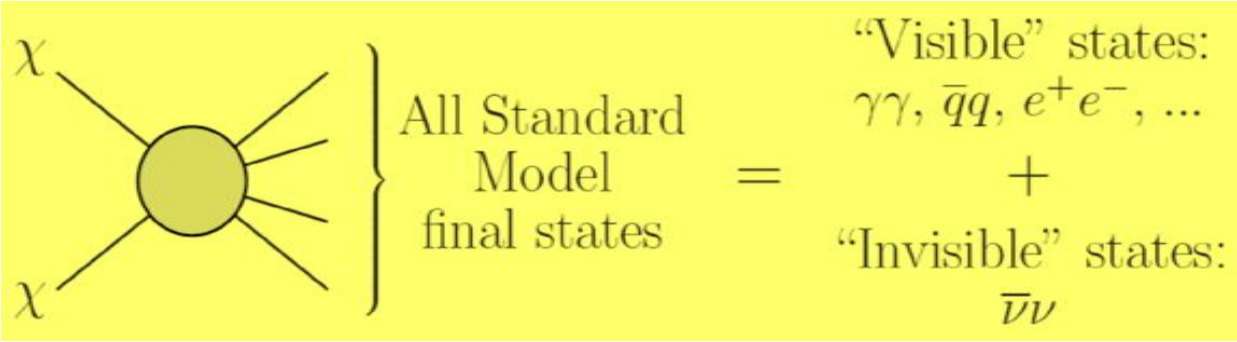
MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

# Model Independent Limit on DM Annihilation Cross Section

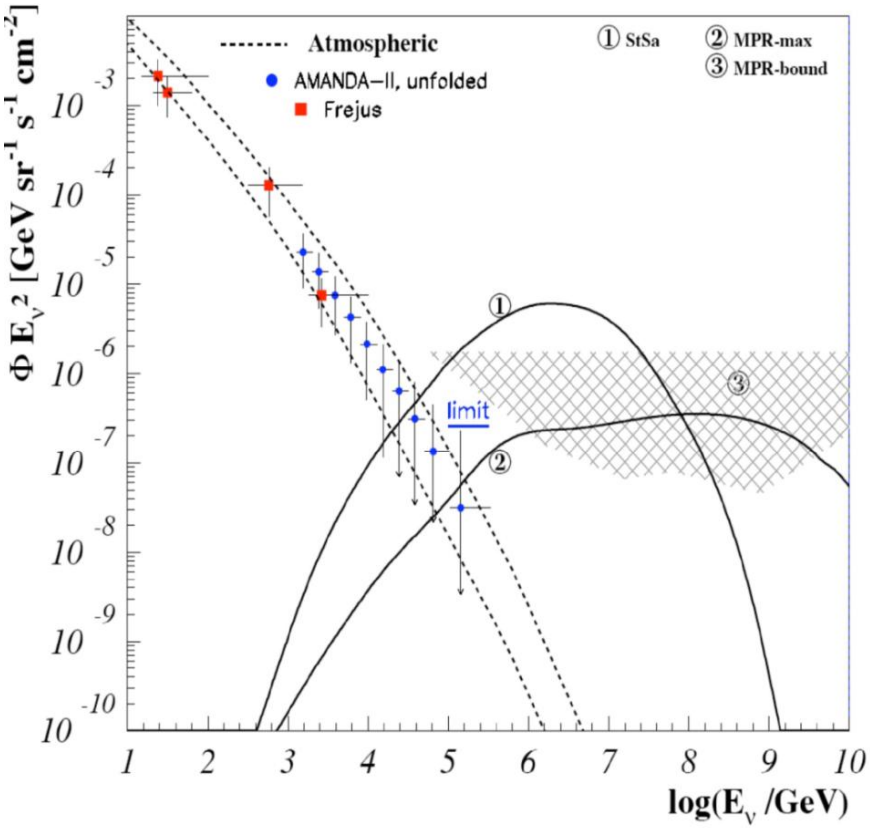
- Assume DM annihilations only produce Standard Model final states

- Stringent upper limit on total annihilation cross section can be obtained by assuming only neutrinos are produced in final states (worst case, least visible)

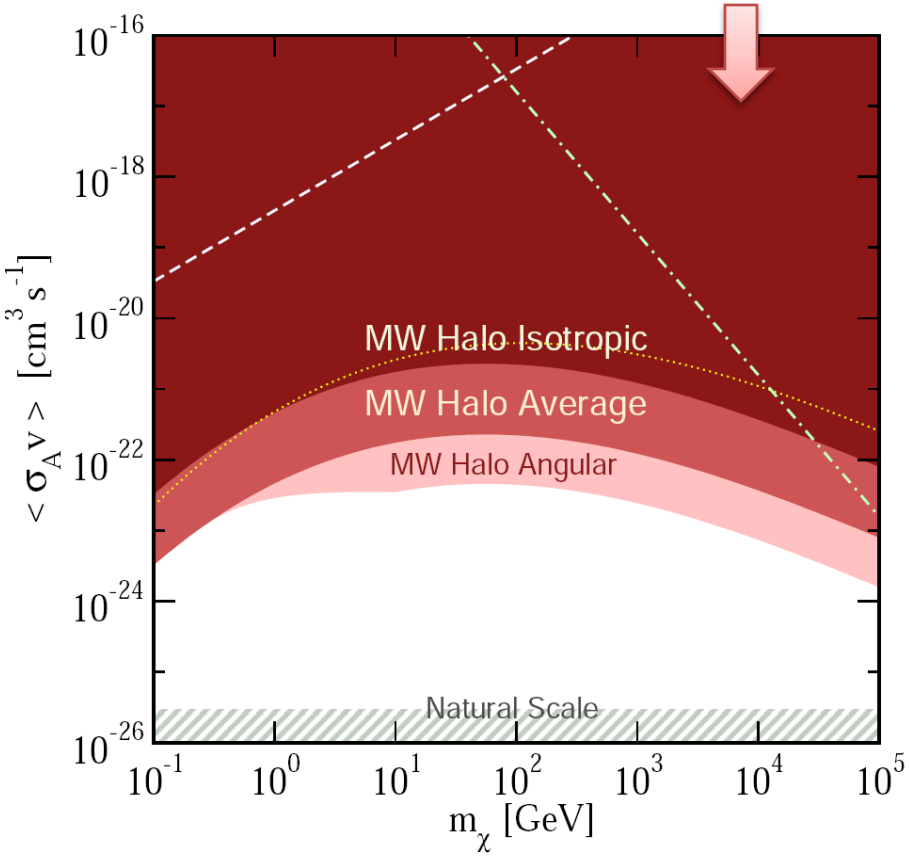



- Anything else will eventually produce much more visible gamma rays (leading to a stronger limit)

# Compare to Atmospheric Nu Flux



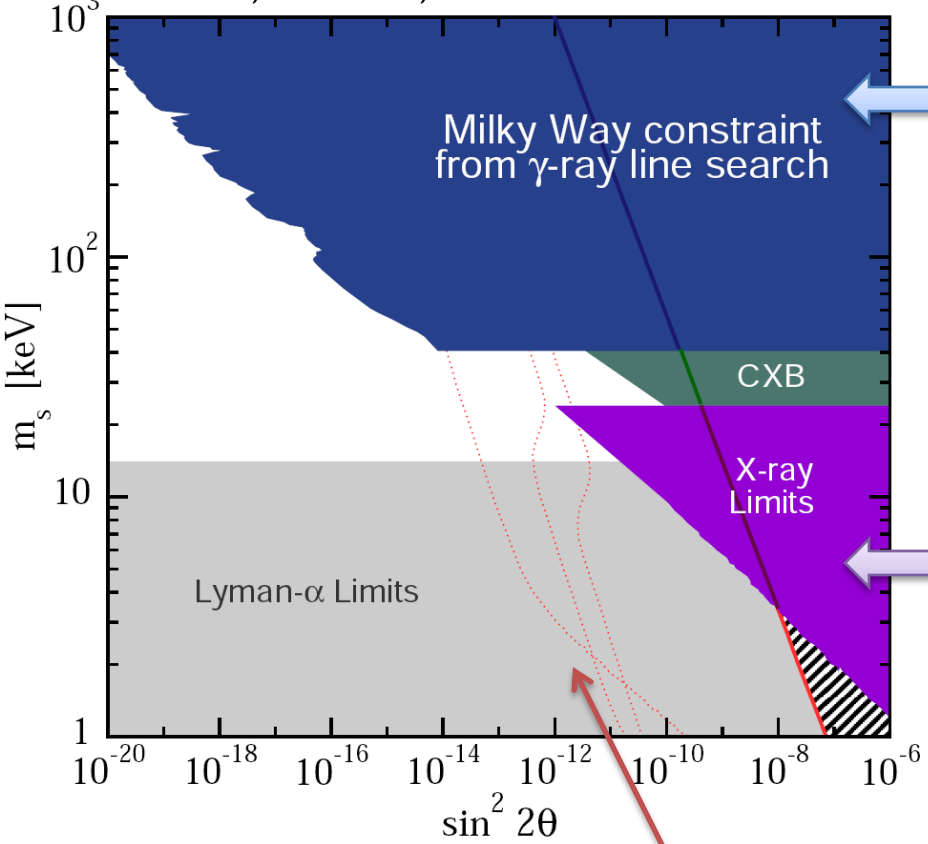

"Even Neutrinos are overproduced"



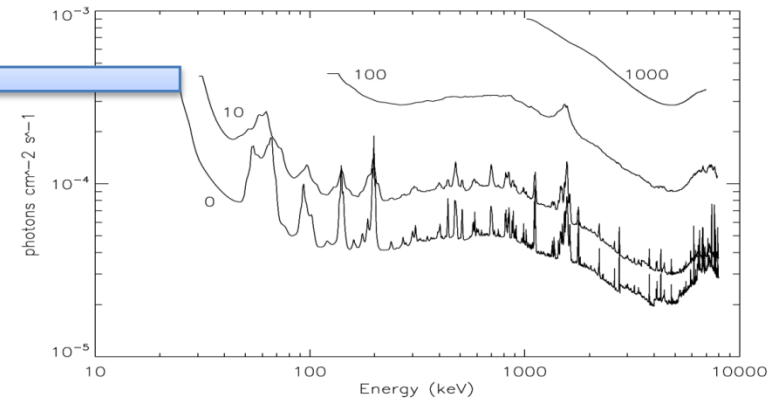

Yuksel, Horiuchi, Beacom, Ando 2007
Beacom, Bell, Mack 2006

# Constraints on sterile neutrino DM

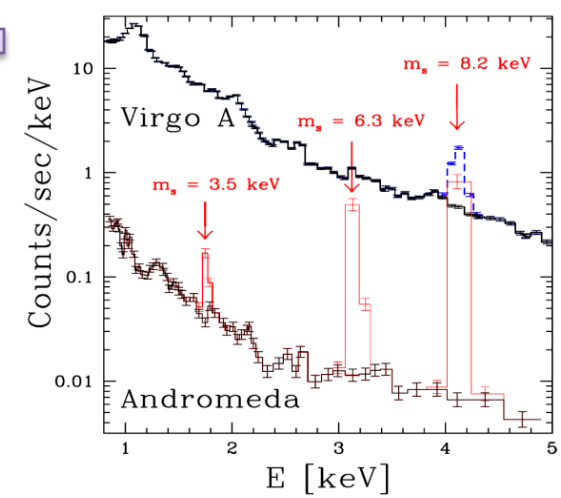
Yuksel, Beacom, Watson 2008




Teegarden, Watanabe2006

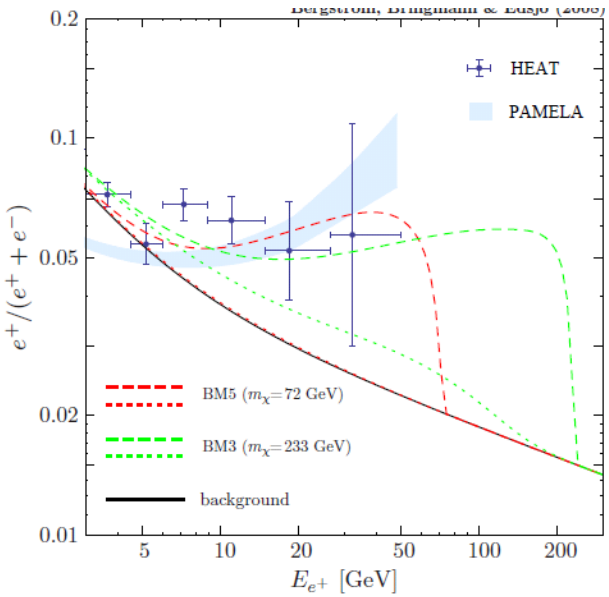


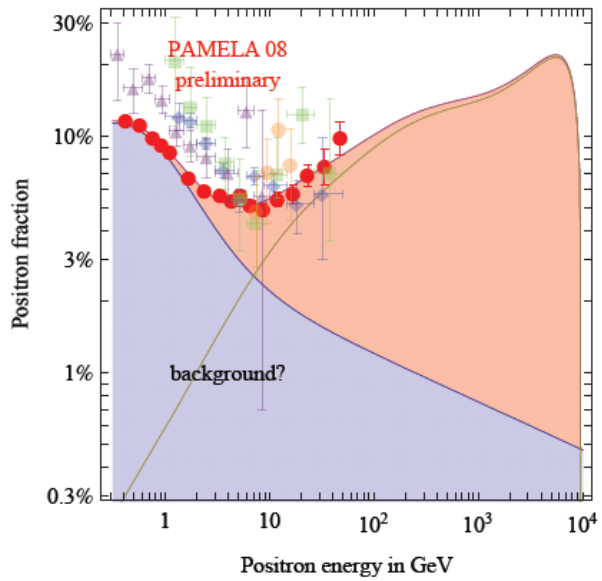

Watson Beacom Yuksel Walker 2006

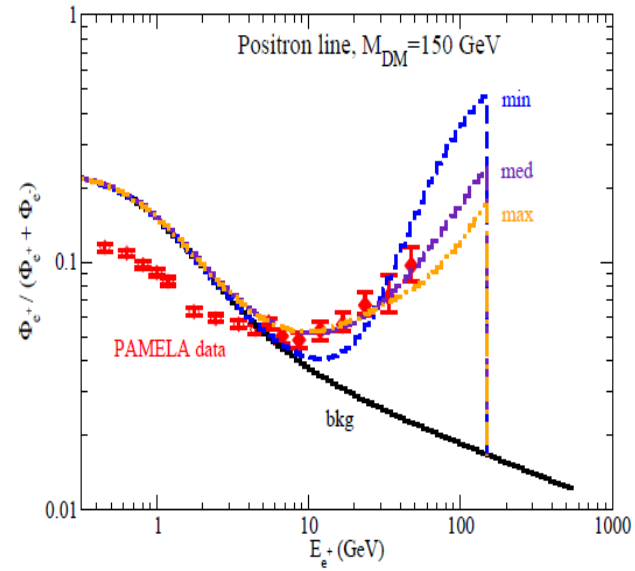


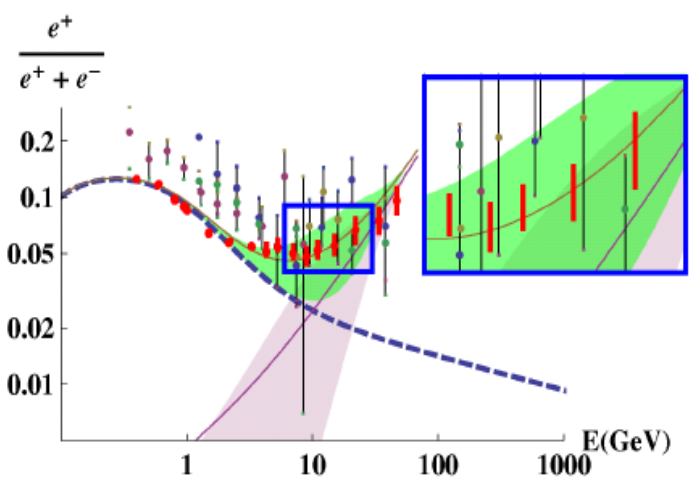

Abazajian, Fuller 2002
Kishimoto, Fuller 2008

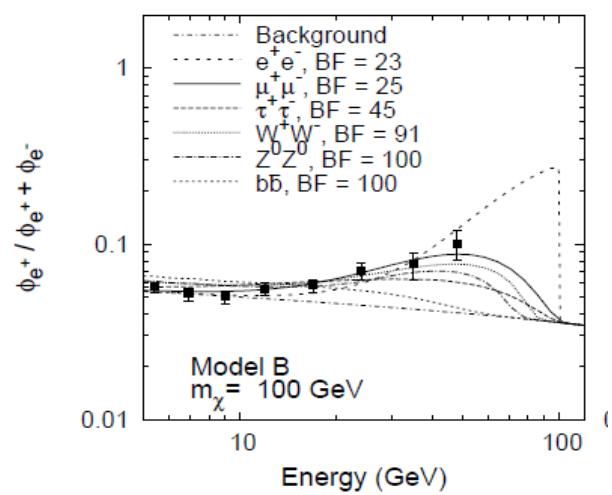
# DM and Multi-GeV Positron Excess



# TeV Gamma Rays From Geminga and Multi-GeV Positron Excess

Hasan Yüksel
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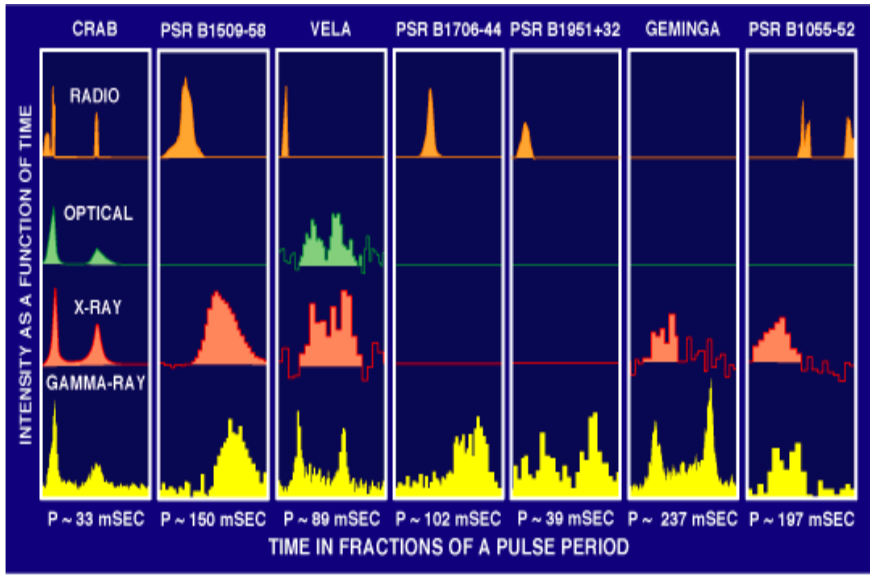
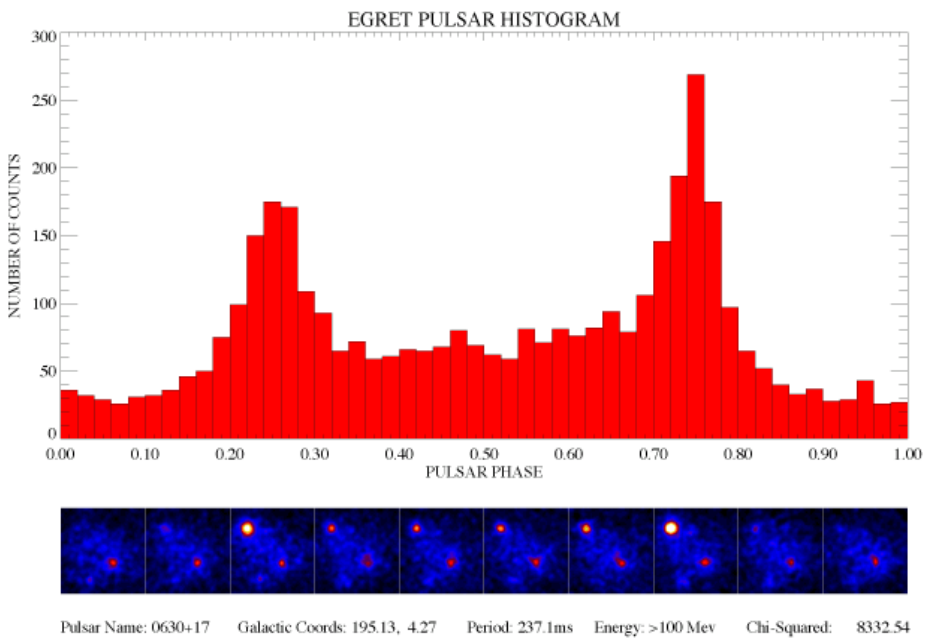
(in collab. with Matt Kistler and Todor Stanev)

# Geminga:

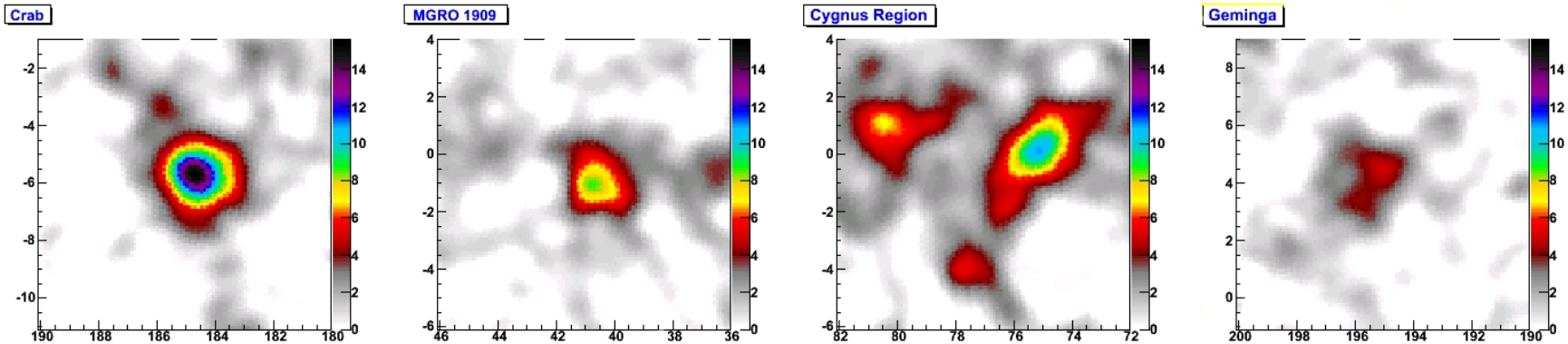
- Radio quite
- First pulsar to be discovered through gamma rays
- Until recently, no evidence of a high energy activity beyond immediate neighborhood

$$r_G \sim 250^{+120}_{-62}\ \mathrm{pc}$$
$$t_G \sim 3 \times 10^5\ \mathrm{yr}$$

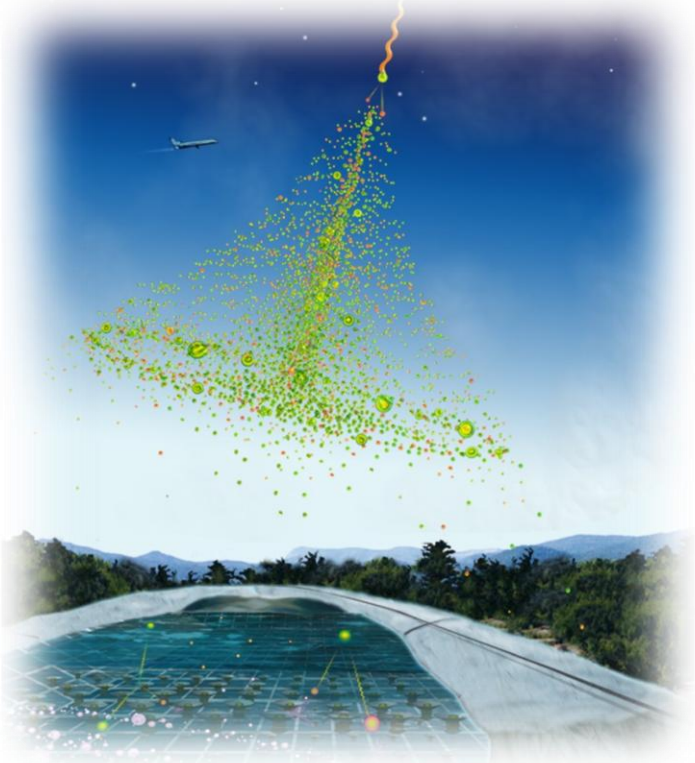


# Milagro Galactic Plane Survey



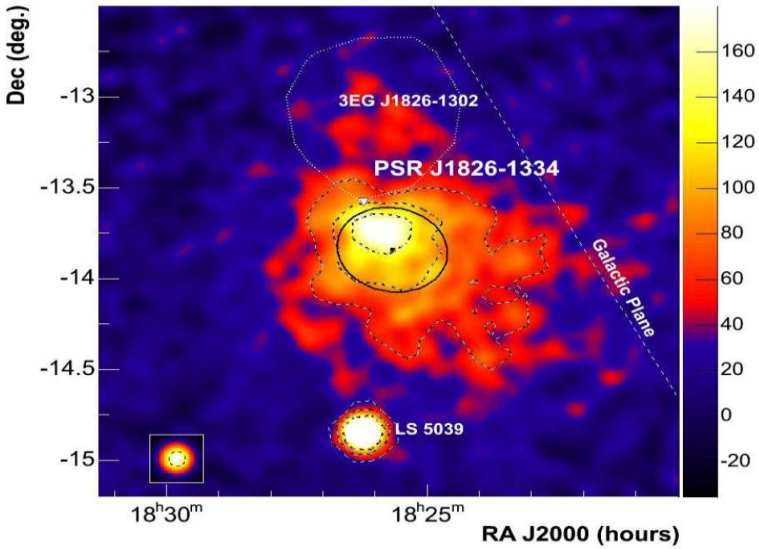

| Object | Location (l, b) | Flux[c] at 20 TeV $\times 10^{-15}$ $TeV^{-1}cm^{-2}s^{-1}$ | Extent Diameter (deg) |
|---|---|---|---|
| Crab | 184.5, −5.7 | $10.9 \pm 1.2$ | - |
| MGRO J2019+37 | 75.0, 0.2 | $8.7 \pm 1.4$ | $1.1^{o} \pm 0.5^{o}$ [d] |
| MGRO J1908+06 | 40.4, −1.0 | $8.8 \pm 2.4$ | $< 2.6^{o}$ (90%$CL$) |
| MGRO J2031+41 | 80.3, 1.1 | $9.8 \pm 2.9$ | $3.0^{o} \pm 0.9^{o}$ |
| C1 | 77.5, −3.9 | $3.1 \pm 0.6$ | $< 2.0^{o}$ (90%$CL$) |
| C2 | 76.1, −1.7 | $3.4 \pm 0.8$ | [e] |
| C3 | 195.7, 4.1 | $6.9 \pm 1.6$ | $2.8^{o} \pm 0.8^{o}$ |
| C4 | 105.8, 2.0 | $4.0 \pm 1.3$ | $3.4^{o} \pm 1.7^{o}$ |



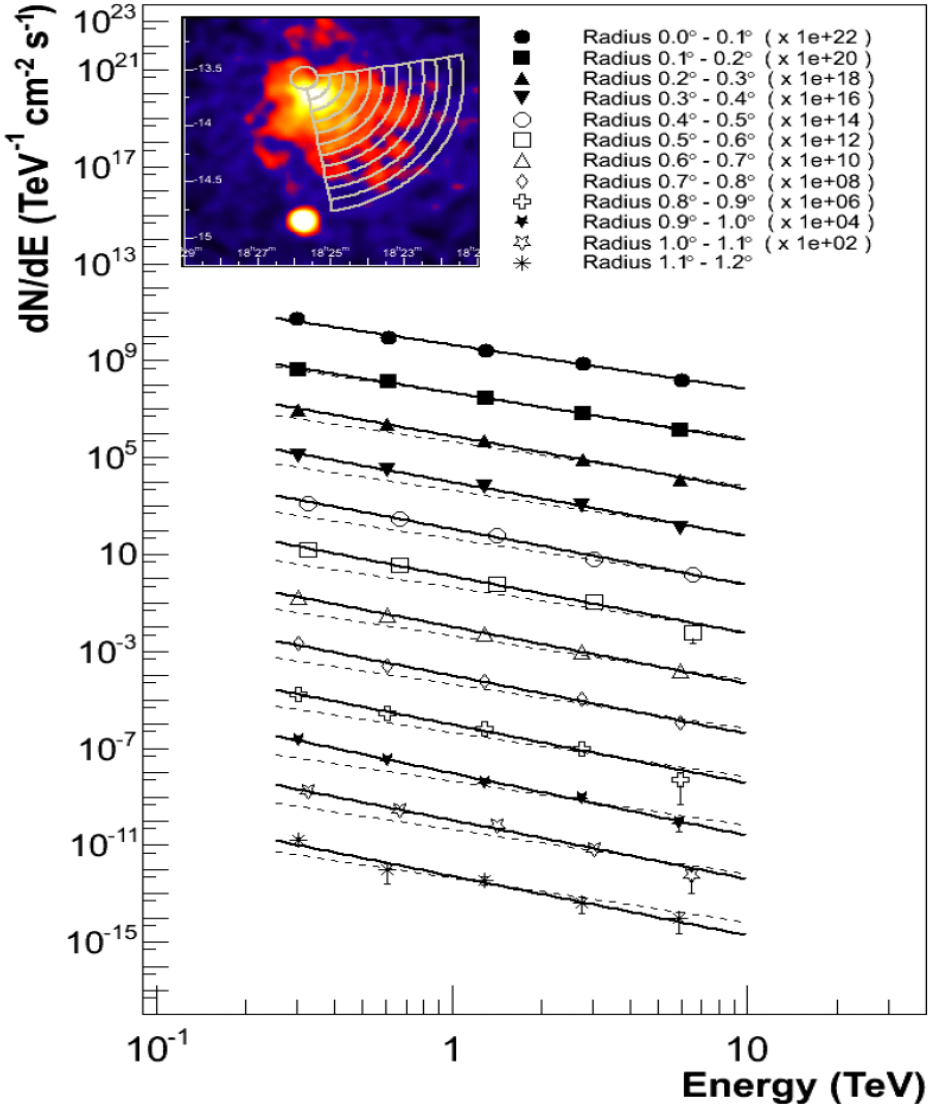
# Immediate Implications:

- Milagro detection puts Geminga among growing class of TeV PWNe
- Detection of TeV gamma rays indicates the existence of a nearby cosmic ray accelerator:
  - If gamma rays have a <u>leptonic</u> origin, the source is young & close enough to make a plausible contribution to CR positrons
  - Alternatively, a neutrino signal would be expected from a <u>hadronic</u> source

# More Distant PWN by HESS




HESS J1825-137, Aharonian et al.

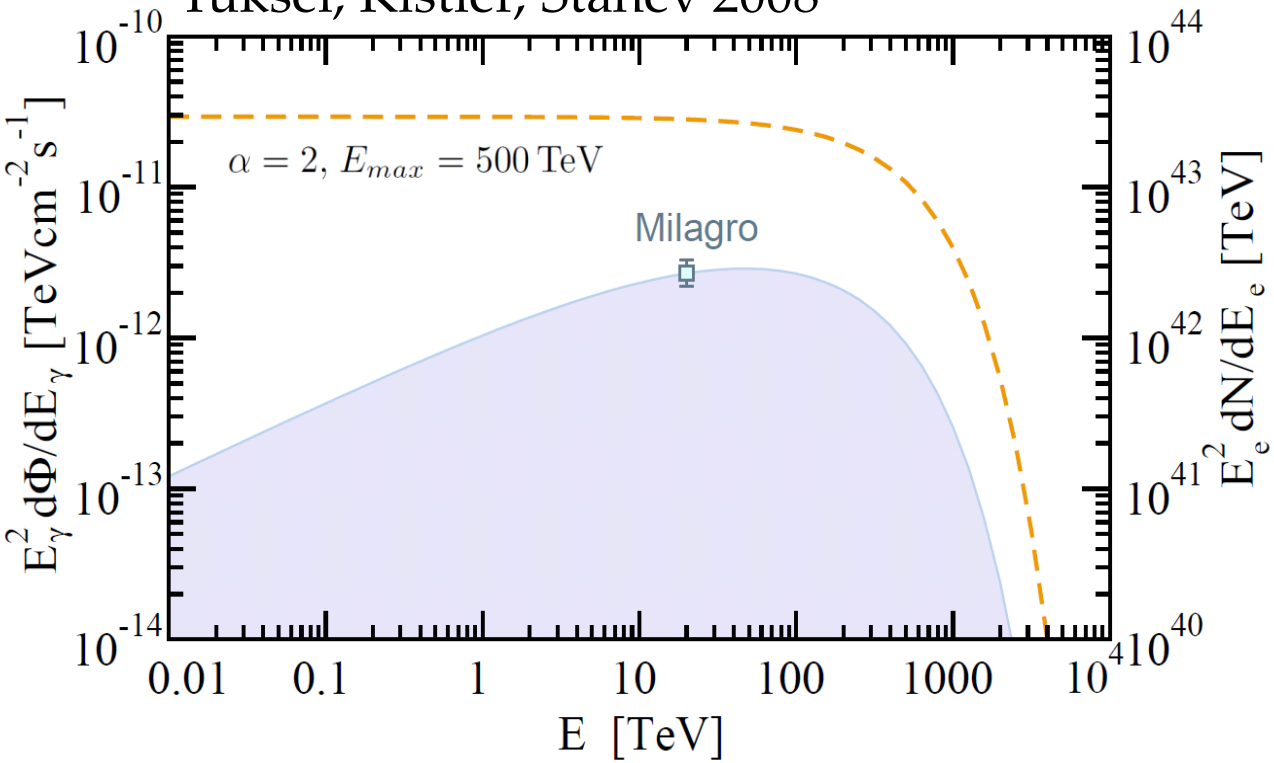


# TeV Gamma Rays from Geminga

$$dN/d\gamma = N_0 \gamma^{-\alpha} e^{-\gamma/\gamma_{max}} \qquad \gamma_{max} = E_{max}/(m_e c^2)$$

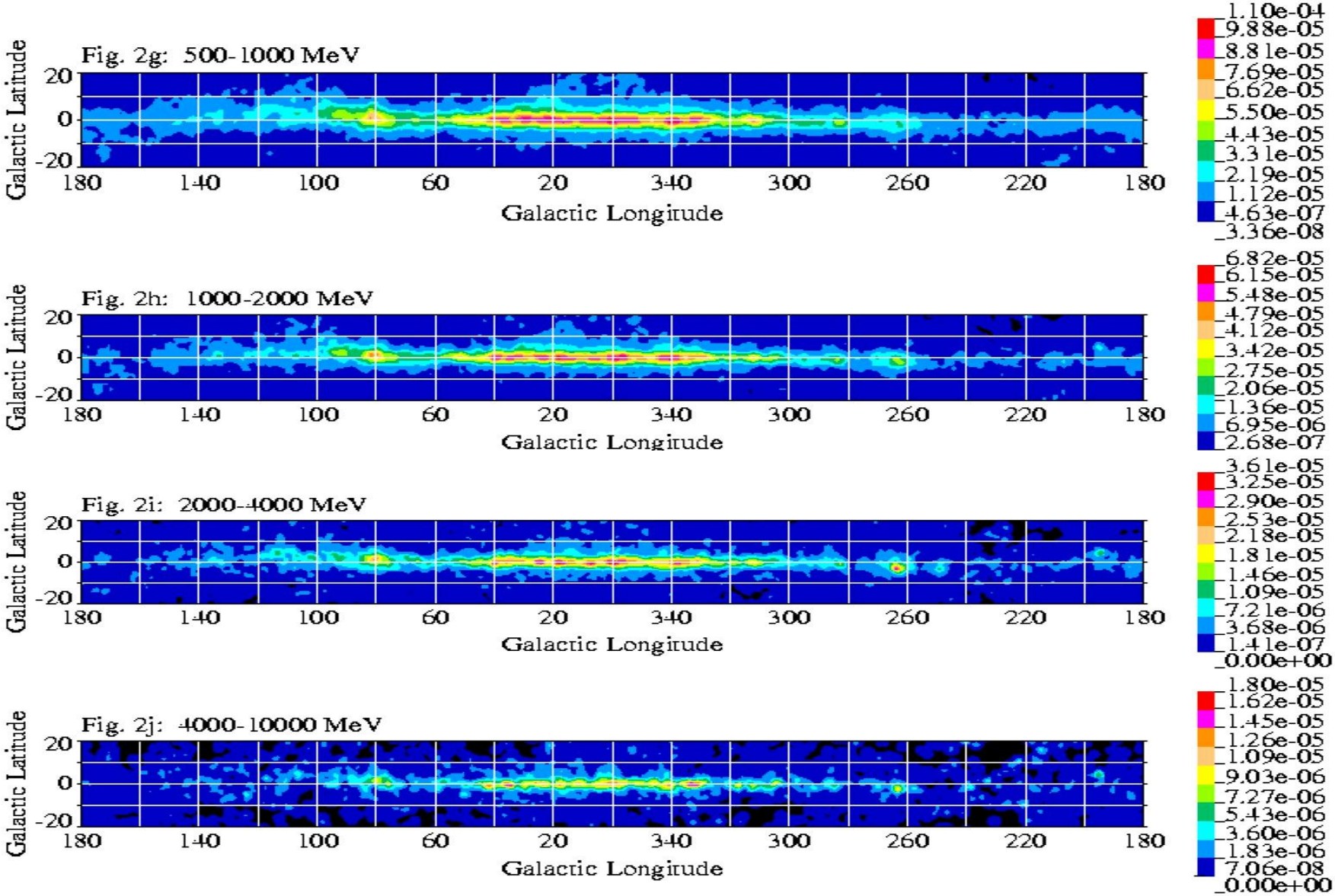
$$\frac{d\Phi}{dE_\gamma} = \frac{c}{4\pi r_G^2} \int d\gamma \int dE_{ph} \frac{dN}{d\gamma} n_{ph}(E_{ph})\, \sigma_{KN}(\gamma, E_{ph}, E_\gamma)$$

Yuksel, Kistler, Stanev 2008

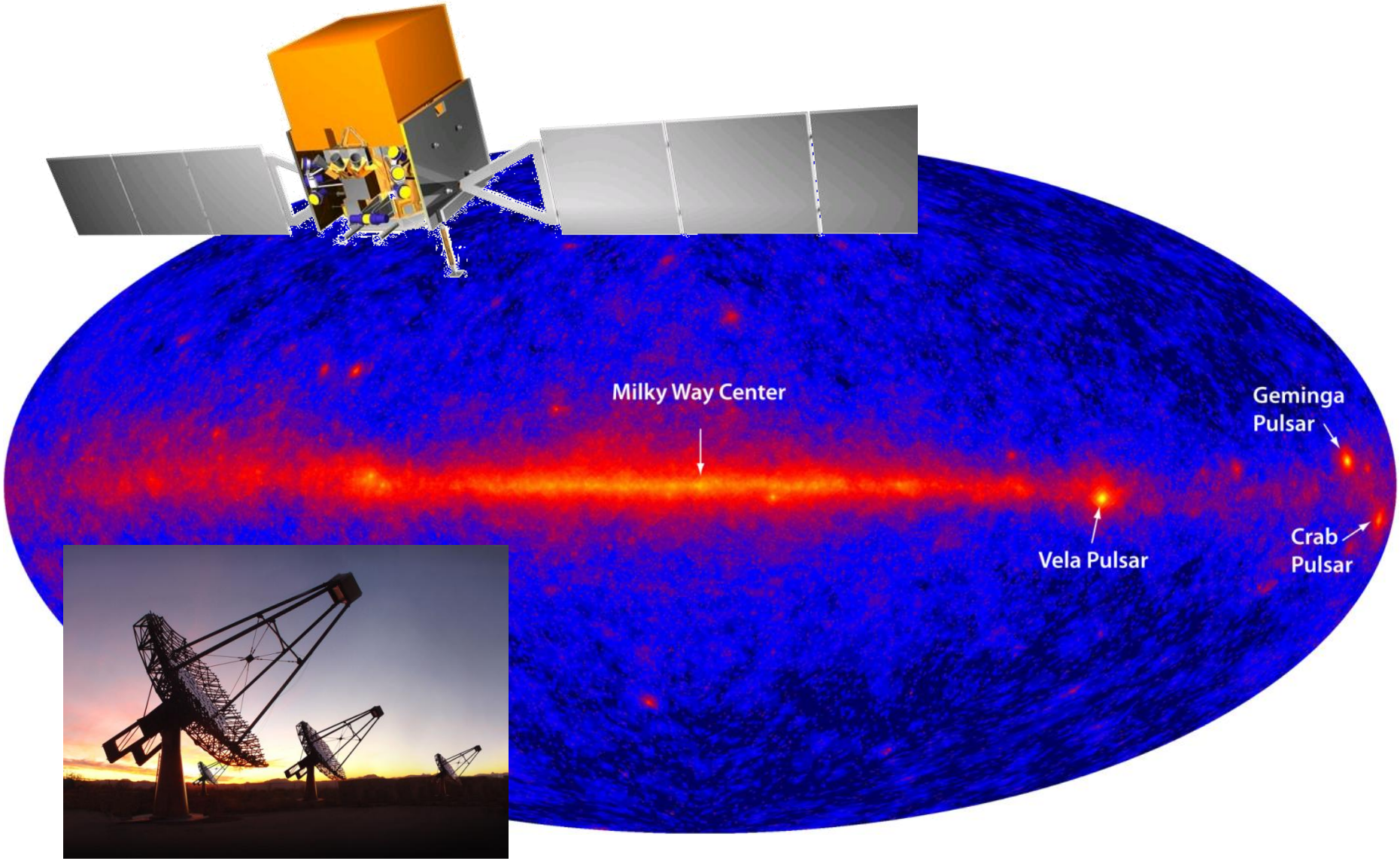



$$\mathcal{E}_e(\gtrsim 1\,\mathrm{GeV}) \simeq 10^{45}$$

# Galactic Plane by EGRET



# Fermi (GLAST) / Veritas Prospects



# Positron Injection to ISM & Diffusion

$$\boxed{\frac{\partial n}{\partial t} = \frac{\mathcal{D}(\gamma)}{r^2}\frac{\partial}{\partial r}r^2\frac{\partial n}{\partial r} + \frac{\partial}{\partial \gamma}[\ell(\gamma)\, n] + Q(\gamma)}$$

$$\mathcal{D}(\gamma) = \mathcal{D}_0(1+\gamma/\gamma_*)^\delta \qquad \mathcal{D}_0 \simeq 4\times 10^{27}\ \mathrm{cm}^2\mathrm{s}^{-1}$$

$$\gamma_* \simeq 6\times 10^3,\ \delta \simeq 0.6$$

$$\ell(\gamma) = \ell_0\gamma^2 \qquad \ell_0 \simeq 5\times 10^{-20}\ \mathrm{s}^{-1}$$

$$Q(\gamma) = dN/d\gamma\, \delta(r)\, \delta(t-t_G)$$

Atoyan, Aharonian, Volk, 1995

$$\boxed{n(r,t,\gamma) = \frac{dN/d\gamma}{\pi^{3/2}\, r^3}\frac{(r/r_d(t,\gamma))^3\, e^{-(r/r_d(t,\gamma))^2}}{(1-\ell_0\, t\, \gamma)^{2-\alpha}}}$$

$$r_d(t,\gamma) \simeq 2\left(\mathcal{D}(\gamma)[1-(1-\gamma/\gamma_c)^{1-\delta}]/[(1-\delta)\gamma/\gamma_c]\right)^{1/2}$$

$$E = 2\,(10,50)\ \mathrm{GeV} \qquad r_d \simeq 150\,(200,300)\ \mathrm{pc}$$

# Local Positrons from a Nearby Continuously Emitting Source

$$n_\odot(\gamma) = \int^{t_G} dt\, n(r_G, t, \gamma) \qquad d\dot{N}/d\gamma = \dot{N}_0 \gamma^{-\alpha} e^{-\gamma/\gamma_{max}}$$

$$\dot{N}_0 = \mathcal{L}_e(t) \left( m_e c^2 \int_{\gamma_{min}} \gamma^{-\alpha+1} e^{-\gamma/\gamma_{max}} d\gamma \right)$$

Assuming breaking via magnetic dipole radiation:
Pulsar spin down luminosity evolves as $\propto (1 + t/t_0)^{-\frac{n+1}{n-1}}$

The injection rate of relativistic e-e+ by Geminga:

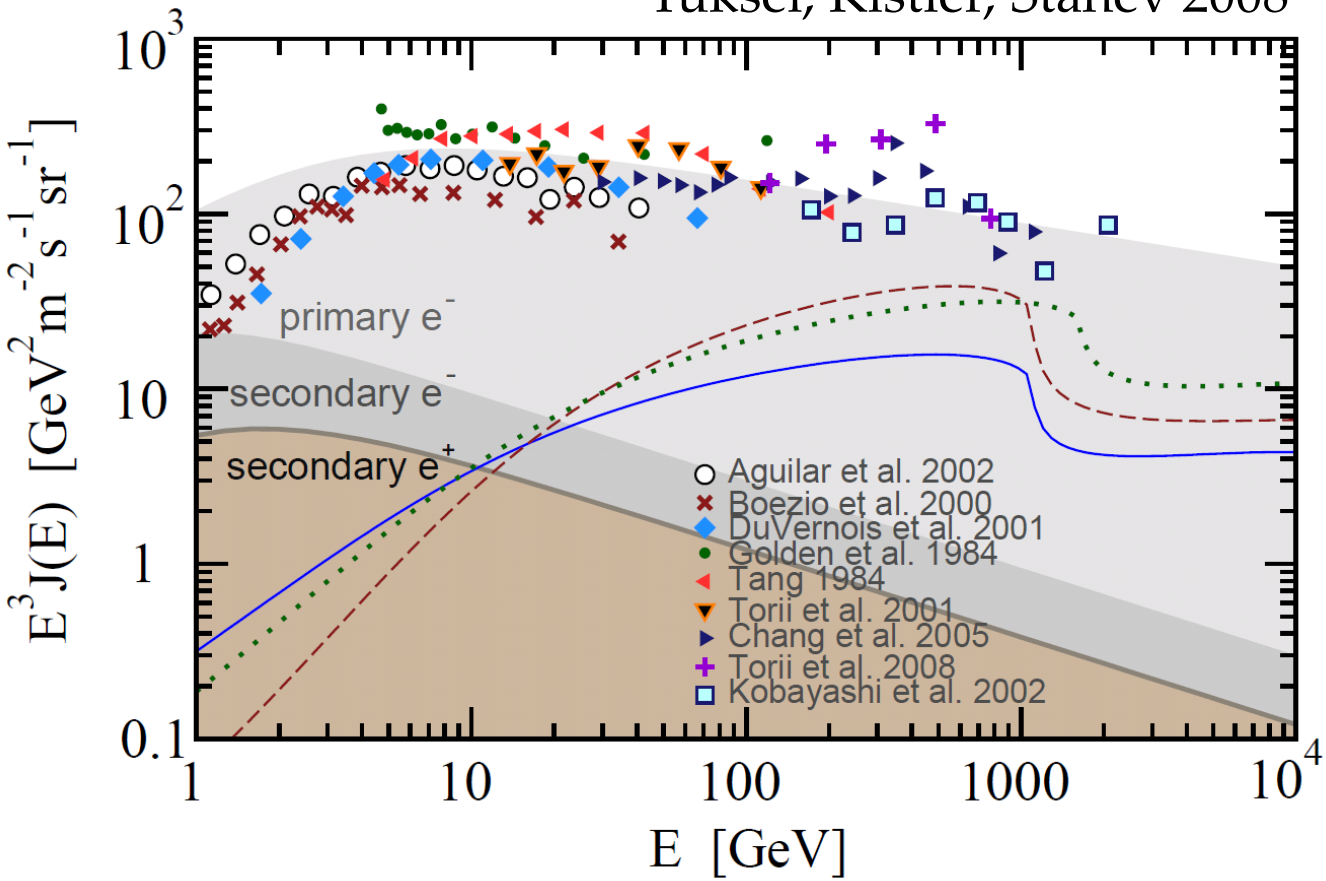
$$\mathcal{L}_e(t) = \frac{\mathcal{E}_G}{t_G} \frac{(1 + (t_G - t)/t_0)^{-2}}{\int^{t_G} dt' (1 + (t_G - t')/t_0)^{-2}}$$

Geminga was much stronger in the past and dominated the TeV sky: Multi-GeV positrons may still be reaching us today

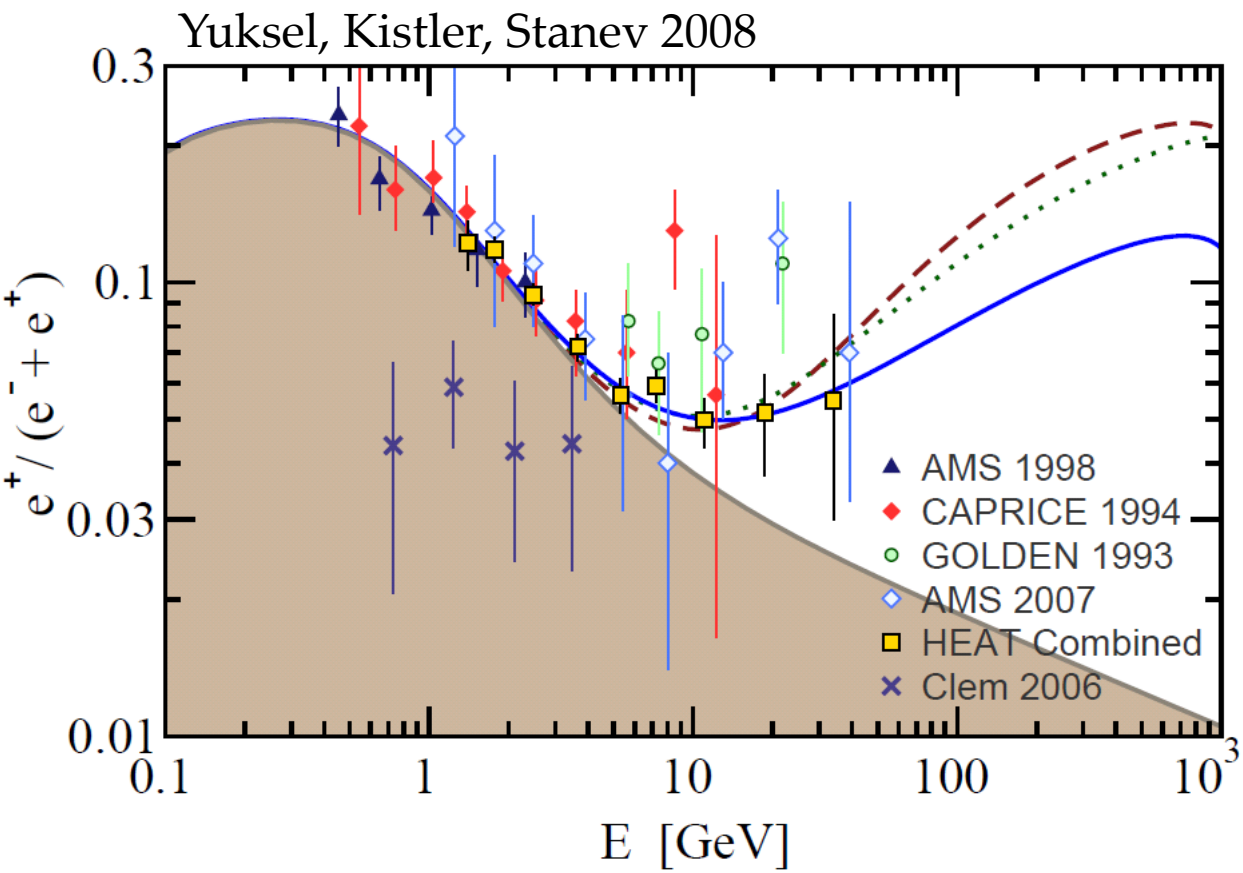
# Background Cosmic Ray Fluxes & Plausible Geminga Contributions

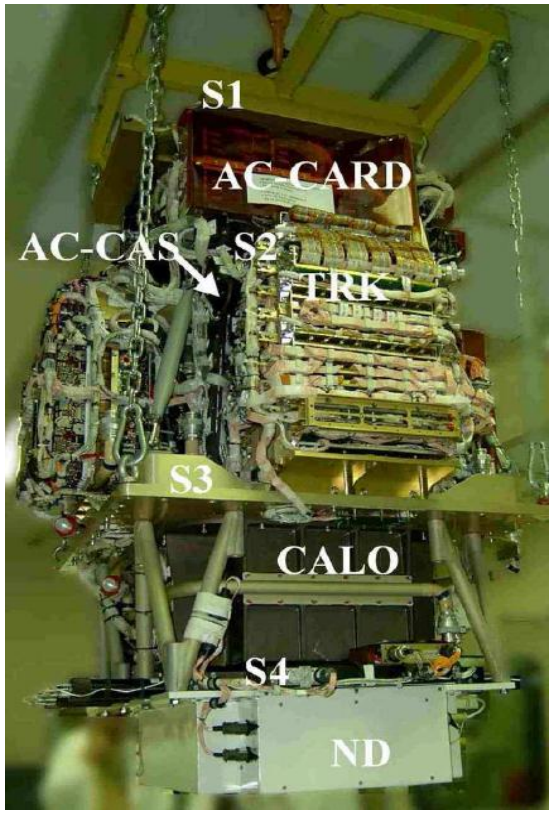
$$t_G = 3\,(3,2) \times 10^5 \text{ yr} \quad \mathcal{E}_G \simeq 2\,(5,2) \times 10^{48} \text{ erg} \quad r_G = 2\,(3,2) \times 10^2 \text{ pc}$$

Yuksel, Kistler, Stanev 2008



# Accounting for Positron Excess?

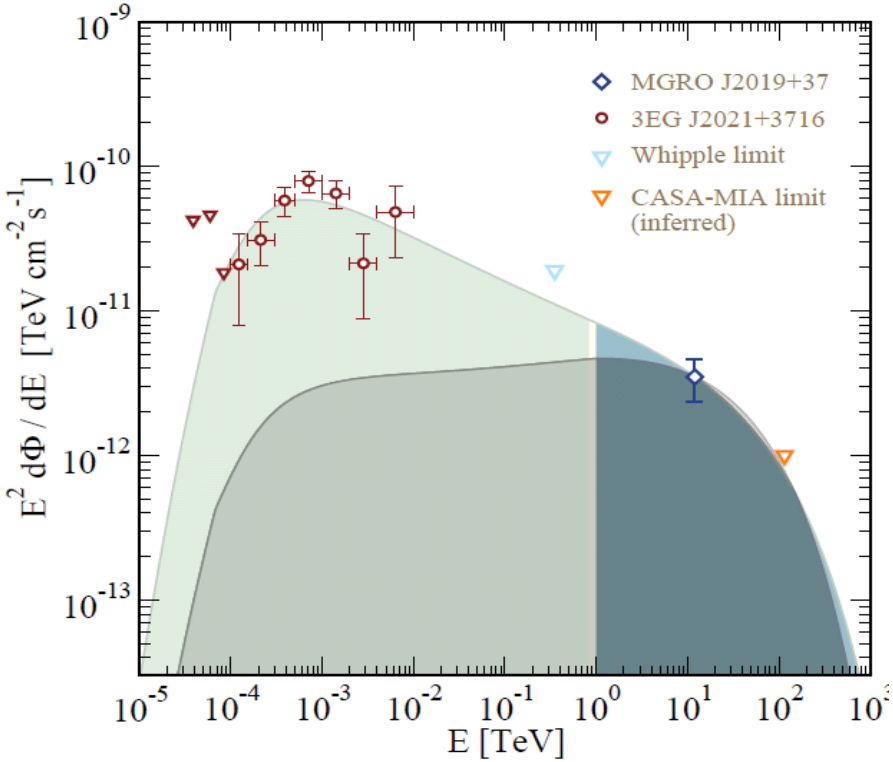


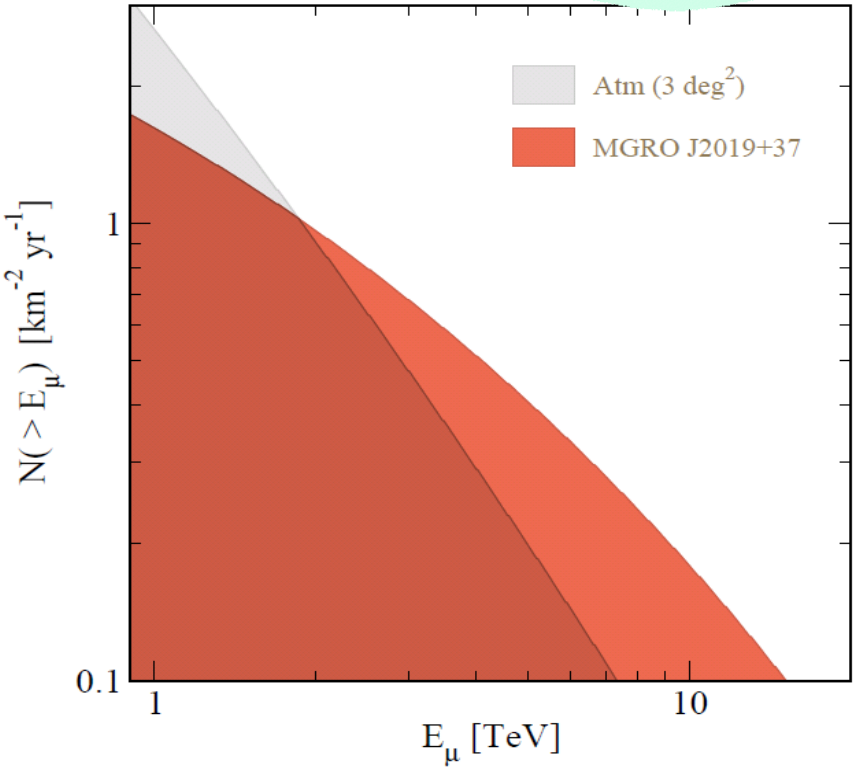




PAMELA should yield an improved picture of the positron fraction

# Hadronic Alternative: TeV Neutrinos

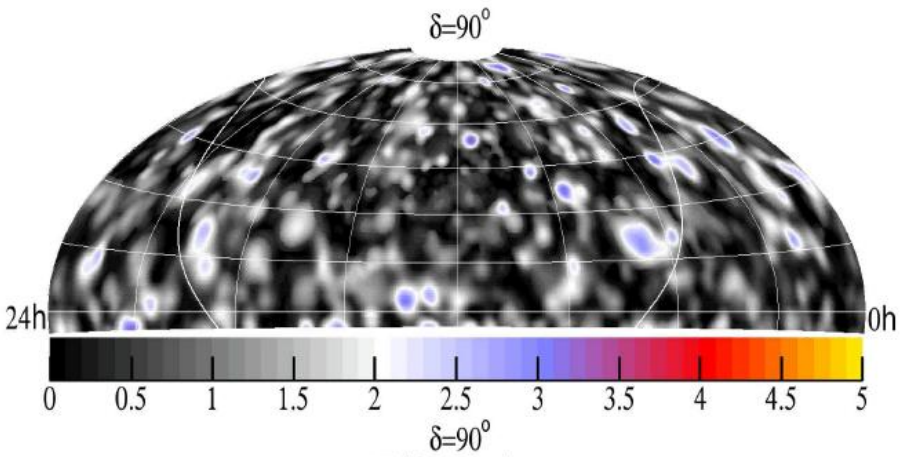
- If a nucleonic wind carry away much of the spin down energy of pulsar, gamma rays may be produced via decay of neutral pions from hadronic scattering
- ➔ >1 Neutrino-induced muon in IceCube

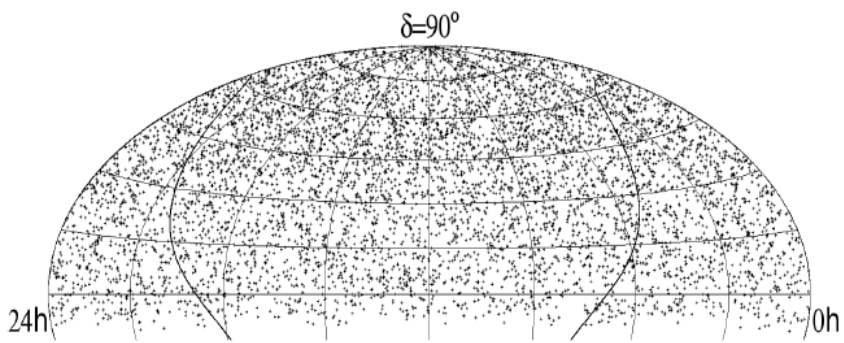



Beacom, Kistler 2007

# Amanda-II Hot(test) Spot




| Candidate | $\delta(^\circ)$ | $\alpha(h)$ | $\Phi_{90}$ | $p$ | $\Psi(^\circ)$ |
|---|---|---|---|---|---|
| 3C 273 | 2.05 | 12.49 | 8.71 | 0.086 | 2.1 |
| SS 433 | 4.98 | 19.19 | 3.21 | 0.64 | 2.2 |
| GRS 1915+105 | 10.95 | 19.25 | 7.76 | 0.11 | 2.3 |
| M87 | 12.39 | 12.51 | 4.49 | 0.43 | 2.3 |
| PKS 0528+134 | 13.53 | 5.52 | 3.26 | 0.64 | 2.3 |
| 3C 454.3 | 16.15 | 22.90 | 2.58 | 0.73 | 2.3 |
| Geminga | 17.77 | 6.57 | 12.77 | 0.0086 | 2.3 |
| Crab Nebula | 22.01 | 5.58 | 9.27 | 0.10 | 2.3 |
| GRO J0422+32 | 32.91 | 4.36 | 2.75 | 0.76 | 2.2 |
| Cyg X-1 | 35.20 | 19.97 | 4.00 | 0.57 | 2.1 |
| MGRO J2019+37 | 36.83 | 20.32 | 9.67 | 0.077 | 2.1 |
| 4C 38.41 | 38.14 | 16.59 | 2.20 | 0.85 | 2.1 |
| Mrk 421 | 38.21 | 11.07 | 2.54 | 0.82 | 2.1 |
| Mrk 501 | 39.76 | 16.90 | 7.28 | 0.22 | 2.0 |
| Cyg A | 40.73 | 19.99 | 9.24 | 0.095 | 2.0 |
| Cyg X-3 | 40.96 | 20.54 | 6.59 | 0.29 | 2.0 |
| Cyg OB2 | 41.32 | 20.55 | 6.39 | 0.30 | 2.0 |
| NGC 1275 | 41.51 | 3.33 | 4.50 | 0.47 | 2.0 |
| BL Lac | 42.28 | 22.05 | 5.13 | 0.38 | 2.0 |
| H 1426+428 | 42.68 | 14.48 | 5.68 | 0.36 | 2.0 |
| 3C66A | 43.04 | 2.38 | 8.06 | 0.18 | 2.0 |
| XTE J1118+480 | 48.04 | 11.30 | 5.17 | 0.50 | 1.8 |
| 1ES 2344+514 | 51.71 | 23.78 | 5.74 | 0.44 | 1.7 |
| Cas A | 58.82 | 23.39 | 3.83 | 0.67 | 1.6 |
| LS I +61 303 | 61.23 | 2.68 | 14.74 | 0.034 | 1.5 |
| 1ES 1959+650 | 65.15 | 20.0 | 6.76 | 0.44 | 1.5 |

# Conclusions

- More data should become available soon:
  - GeV Gamma Rays: Fermi (GLAST)
  - TeV Gamma Rays: Veritas, Future ACTs
  - Multi-GeV Positrons: PAMELA, AMS?
  - TeV Neutrinos: IceCube
- Which may result in:
  - Developing more detailed models, including time & spatial evolution in the source
  - Unraveling Multi-GeV positron excess?
  - Discovering First TeV neutrinos source?